

Multi-Way LED-Based Surface Reflectance Sensor and Spectrophotometer

Related Application

[01] This application is a Continuation-in-Part Application of U.S. Patent Application 10/251,251, titled "Multi-Way LED-Based Chemochromic Sensor," filed by Yerazunis et al. on September 20, 2002.

Field of the Invention

[02] This invention relates generally to surface reflectance sensors and more particularly to LED-based surface reflectance sensors and spectrophotometers

Background of the Invention

[03] With a surface reflectance sensing system, a material to be tested is illuminated by a light source, and reflected light is measured with a light sensor. The light can be monochromatic, a range of wavelengths, or a mixture of wavelengths, such as 'white' light. This can be accomplished either by filtering the emitted light or the sensed light.

[04] For example, the light source can be a wide-band tungsten-halogen or a tungsten-deuterium light that is filtered. The filtered light is transmitted to the surface, and then reflected and carried back to a sensor via an optical fiber. The wavelengths can be separated by a slit and diffraction grating, and measured by a photodiode array or CCD array and an analog-to-digital (A/D) converter. Depending on a width of the slit and a fineness of the diffraction grating, a

resolution of 1 to 4 nanometers can be attained across a range of 350 to 1100 nanometers. There, the A/D converter is the most expensive component of the system.

[05] In another surface reflectance system, narrow-band LEDs are used to emit light at known wavelengths, and photodiodes and an A/D circuit are used to measure the reflected light. Although, that type of system is less expensive, the small number of available colors available, e.g., five, makes it less suitable for analytical work.

[06] LED-based systems have been used for color matching in the graphic arts, printing, photocopying, publishing, and paint-matching trades.

[07] All of the prior art systems use conventional A/D circuits. In such circuits, the phototransistor or photodiode is a light-controlled current source or light-controlled resistor. The current generated by the photodiode device is amplified and directly measured by the A/D converter. Because the directly measured instantaneous current is typically only a few microamperes, a sensitive, low-noise amplifier must be used. That substantially increases the expense, size and power requirements of the system.

[08] In addition, silicon photodiodes have a peak sensitivity at roughly 670 to 700 nanometers, extending into deep infrared, and are relatively insensitive to blue and ultraviolet light. Therefore, a proportional filter is used to 'flatten' the response to match that of the human eye, which decreases the sensitivity of the system. Furthermore, the dynamic range of a conventional 16-bit converter is roughly 64,000 : 1, with a considerable power consumption.

[09] Therefore, there is a need for surface reflectance sensors and spectrophotometers that overcome the problems of the prior art.

Summary of the Invention

[010] The present invention provides an inexpensive surface reflectance sensing system with a high dynamic range, and a low power requirement. The system is particularly suited for applications where there is a minimal amount of light.

[011] The invention replaces the prior art amplifier and A/D converter with a simple thresholding circuit. In this circuit, pairs of photodiodes, preferably LEDs, are directly connected to corresponding digital input/output (I/O) pins of a microcontroller, which is controlled by software.

[012] Current delivered by the I/O pins set the cathode of the LED to a logical 1, nominally +5 volts for TTL compatible parts, and the anode to a logical 0, i.e., 0 volts. One photodiode emits light onto a surface of a material to be tested when switched in a forward bias state, while the other photodiode senses reflected light when first charged in a reverse bias state, and then allowed to discharge.

[013] In the reverse bias state, an internal parasitic junction capacitance of the LED is charged. The junction capacitance varies, on the order of 20 picofarads. The imposed voltage is due to the varactor effect. The parasitic capacitance can also include capacitance inherent in the microcontroller I/O pins and connective

wiring. Assuming a capacitance of 20 pFarads and 5 volts, approximately 100 picoCoulombs of charge is stored in the junction.

[014] After the junction capacitor is fully charged, which takes only a few microseconds, the microcontroller I/O pin is switched to a high impedance input state, e.g., one million Ohms to 250 giga-Ohms. Even in this high-impedance state, the I/O pin can still be 'read' by the software. If the voltage on the I/O pin is greater than a predetermined logic threshold voltage, e.g., + 1.7 volts, then the input at the pin is read as a logical '1', and otherwise, the input is read as a logical '0'. In the high-impedance mode, it takes several seconds to discharge the 20 picofarad LED junction capacitance from +5 volts down to the digital logic threshold of 1.7 volts when the current drain is minimal, that is, absent the presence of incident light. In full sunlight, the current drain can be on the order of one microampere.

[015] A polling program or an interrupt service procedure in the microcontroller can measure the amount of time it takes to discharge the junction from +5 volts down to the threshold voltage of 1.7 volts. This time is inversely proportional to the amount of incident light. In bright light, e.g., direct sunlight, the discharge takes only a few microseconds. In a moderately lit environment, the discharge takes about 100 milliseconds, and under minimal lighting, the discharge can take several seconds.

[016] The very wide dynamic range of the sensor system according to the invention, i.e., several million to one, greatly exceeds the dynamic range of any prior art surface reflectance sensors that use amplifiers and A/D converters.

[017] As an advantage, an LED is generally equally sensitive to all wavelengths equal or shorter than an emission wavelength of the LED. Light at longer wavelengths generates significantly less photocurrent. For example, a yellow LED responds almost equally well to yellow, green, blue light, and ultraviolet light, but does not respond to orange, red, or infrared light. Therefore, a very inexpensive coarse-resolution spectrograph can be constructed by using concurrently several LEDs tuned to different colors.

[018] In this embodiment, each LED sensor responds only to wavelengths equal to or shorter than the emission wavelength of the sensor. Thus, it is possible to reconstruct the per-band light intensities, or spectra, of the incident light.

[019] As an additional advantage, the LEDs can be switched rapidly between emitting and sensing modes. In this way, longer-wavelength LEDs can be used both as sensors for shorter wavelength LEDs, as well as emitters for yet longer wavelength LEDs. In this configuration, material to be tested reflects emitted light to one or more sensor LEDs. Thus, the LEDs can operate as narrow-band emitters and as a high-pass sensor using the same circuit.

[020] As another advantage, a filtering element, such as a UV-blocking filter, can be added so that the system operates as a fluorescence sensor. In this embodiment, a widest-band-sensitivity LED is used, e.g., a red or infrared LED, which can sense respectively all visible light, or all visible and near infrared wavelengths. More than one LED can be used with the UV-blocking filter to provide a coarse resolution fluorescence spectrograph.

[021] This configuration, where a short-wave-blocking filter covers one or more of the sensing LEDs, can detect the presence or absence of small amounts of a material that may fluoresce in either the visible or infrared wavelength ranges.

[022] As another advantage, the LEDs can be switched rapidly between emitting and sensing modes, e.g., less than a microsecond. In this way, differential measurements can be acquired, where the sensor measures transmitted or reflected light in both the presence and absence of an excitation source, and the actual useful signal is a difference function of the two signals.

Brief Description of the Drawings

[023] Figure 1 is a block diagram of a light sensor with a single LED according to the invention;

[024] Figure 2 is a block diagram of a multiple LED light sensor according to the invention;

[025] Figure 3 is a side view of the light sensor of Figure 2;

[026] Figure 4A is a side view of a light sensor and a test material;

[027] Figure 4B is a side view of an alternate light sensor and test material;

[028] Figures 5A is a block diagram of a light sensor for measuring specular reflection;

[029] Figures 5B is a block diagram of a light sensor for measuring diffuse reflection;

[030] Figure 6 is a graph of relative sensitivity of various types of LEDs indicating relative photocurrent as a function of incident light wavelength; and

[031] Figure 7 is a side view of a light sensor for measuring UV fluorescence.

Detailed Description of the Preferred Embodiment

[032] Basic Bi-Directional LED Sensor Circuit

[033] Figure 1 shows an LED-based light sensor 100 according to the invention. The sensor includes an LED 110, a capacitor 120, and a microcontroller 130. An anode 111 of the LED 110 is connected to a bi-directional digital I/O pin 101 of the microcontroller. A cathode 112 is connected to another pin 102. The state of current on the I/O pins 101-102 determines whether the LED 110 emits or senses light. For a detailed description of light emitting diodes operating as both an emitter and a sensor see U.S. Patent Application Sn. 10/126,761 "Communication Using Bi-Directional LEDs," filed by Dietz et al. on April 19, 2002, incorporated herein by reference in its entirety.

[034] The microcontroller 130 can be a MicroCircuits Inc. PIC 16F876 processor, which has multiple data pins. The microcontroller 100 also has conventional power and communication connections. These connections are not shown for clarity. The microcontroller can execute software 135.

[035] In addition, to operate LEDs as described herein, the software also performs timing functions (timer) 136 by either a polling procedure, an interrupt service procedure, or using a clock. The timing function essentially measures the amount of time it takes to discharge capacitance stored in the LEDs by an induced photocurrent. The amount of time is inversely proportional to the intensity of incident light. In the embodiment of the invention where multiple LEDs are used, as described herein, the timer can make these timing measurements in parallel or serially.

[036] When microcontroller pin 101 connected to LED anode 111 is configured as an output at Logic 1 (5.0 volts), and microcontroller pin 102 connected to LED cathode pin 112 is configured as an output at Logic 1 (0.0 volts) the LED emits light. The current in this circuit is limited by the output drive capability of the microcontroller output pin. This is a small deviation from common practice in that common practice connects the LED cathode pin 112 to a microcontroller pin but connects the anode 111 to +5 volts either directly or through a current-limiting resistor, typically 220 ohms. The conventional practice is to connect the LED anode pin 111 to microcontroller pin 101, but connects the LED cathode pin 102 directly to ground.

[037] The advantage of the circuit 100 is that by configuring microcontroller pin 101 (connected to LED anode 111) an output at logic 0 (grounded), and configuring microcontroller pin 102 (connected to LED cathode 112) as an output at logic 1 (+5.0 volts), the LED 100 is reverse-biased. This does not cause a significant current, but it does charge the parasitic junction capacitance of the LED 110. This parasitic capacitance is typically on the order of 20 picofarads.

[038] After the parasitic capacitance of LED 110 is charged, typically in a few tens of microseconds, the microcontroller pin 102 connected to LED cathode 112 is reconfigured from output mode to input mode. In input mode, the resistance of microcontroller pin 102 to ground is on the order of a million million ohms, i.e., one million mega ohms. In this state, software can read the logic state of pin 102. If the voltage is greater than the logic threshold of the system, e.g., +1.7 volts for TTL-compatible microcontrollers, then the software 135 reads the logic value “1”, otherwise, the software reads the logic value 0.

[039] As time passes, the charge stored on the parasitic capacitance of the LED 110 dissipates slowly. By far, the greatest cause for this dissipation is incident light 140 striking the junction of LED 110. The parasitic capacitance of the LED connected as described above can hold charge above the 1.7 volt logic level for several seconds in a darkened room, but for only a few microseconds when exposed to direct sunlight. Intermediate amounts of light caused intermediate time-to-discharge time durations.

[040] The software 135 is then used to measure the time for the LED 110 to discharge from +5 volts down to the logic threshold at 1.7 volts. By determining the width of the logic 1 pulse, the software can determine an intensity of the light striking LED 110.

[041] Therefore, the circuit in Figure 1 can be operated to directly produce a pulse-width-modulated logic-level signal with the pulse width inversely proportional to the intensity of light 140. This pulse width can be measured by the microcontroller to yield a numerical representation of the intensity of the light 140. Note that at no time is an analog-to-digital converter employed. Note also that the

duration of time measurement is the determining factor of the resolution of the system. It should also be noted that because the photocurrent discharging LED 110 is the major source of current drain in the system, the circuit shown in Figure 1 actually integrates the light falling onto LED 110. Integration of light produces a much greater sensitivity than the instantaneous measurements of the prior art.

[042] In the rare instance where the light incident on the LED 110 is so bright that the decay time is too short for convenient measurement by the microcontroller, an additional capacitor 120 can be added to the circuit to increase the charge to be discharged, thereby lengthening the time required to measure the discharge. In normal use the capacitor 120 is unnecessary, and the internal parasitic capacitance of LED 110 is adequate for correct operation of the system.

[043] Multiple Sensors

[044] Figure 2 shows an LED-based reflectometer 200 according to the invention. In this configuration, the microcontroller 130 is connected to a set of LEDs 110 via multiple pairs of pins 101-102 to measure the light reflectance of a surface 220 under test. Each LEDs is separately controllable to either emit or sense light, or to be inactive. Thus, a first subset of the LEDs, i.e., one or more, can emit light, while a second subset, i.e., one or more, senses light emitted by the first subset. In this embodiment, the LEDs can be tuned to different wavelengths, so that not all of the wavelengths are identical, and the sensing can be done serially or in parallel.

[045] Sensing Reflected Light

[046] As shown in Figure 3, the LEDs can be positioned so that the emitted light beams 201 are approximately aligned onto the same area 301 of the surface 220 being tested. In this configuration, the LEDs can either be placed so as to allow a specular or mirror-like reflection of the light from one LED into the other LED by having a perpendicular angle, or placed at an oblique angle so that no mirror-like reflection occurs.

[047] This circuit can be used in two modes of operation- continuous illumination and differential illumination.

[048] In continuous illumination, one of the LEDs emits light by setting the associated microcontroller pin connected to the LED anode to output a logic 1, and the cathode to output a logic 0. This turns the associated LED “on” in the conventional sense, and emits light along the light beam 201.

[049] The other LEDs in the system are then utilized as described in Figure 1. That is, the LEDs are reverse-biased to charge the internal parasitic junction capacitance, then the microcontroller pin connected to the cathode is switched to high-impedance input mode, and the time required for the capacitance to discharge due to photocurrent is measured by the microcontroller polling the input pin.

[050] If a reproducible set of measured values are needed, then these can be produced by calibrating the system with calibration surfaces.

[051] It should be noted that the LEDs emit relatively narrow-band light, e.g. a bandwidth of less than 50 nm. Therefore, the reflectivity of the surface, as measured by a sensing LED is the reflectivity of the surface at the wavelength emitted by an emitting LED.

[052] By using LED that emit light at different wavelengths, the reflectivity of the surface under test can be measured.

[053] Further, by altering the relative positions of the LEDs, with respect to each other and in respect to test surface, the reflectivity of the surface under test can be measured both in respect to the diffuse Lambertian, sometimes called 'matte' reflectivity, as well as the mirror-like, glossy, specular reflection.

[054] Differential Measurements

[055] In the differential mode of operation, measurements of the light levels are performed both with an LED or some other light source providing illumination to surface 220, and with no LED providing illumination to surface. The later illumination relies only on ambient natural light from the environment. A difference between the two measurements, i.e., illuminated and ambient-only, provides a way to cancel effects of changing ambient illumination, when this sequence is repeated for each measurement over time.

[056] If in the differential mode, and the ambient and LED-illuminated measurements alternate, a fluctuating ambient source, at a similar frequencies, can interfere in the measurements. In this embodiment, whether each measurement is ambient or LED-illuminated, can be selected by a pseudo-random sequence (PRS),

and averaged over a suitable time period. Any ambient interfering source that does not follow the same pseudo-random sequence is averaged out.

[057] With a careful rearrangement, it is also possible to have all of the LEDs substantially within the domain of specular reflection of each other. In this embodiment, the system measures specular rather than diffuse reflection. This can be accomplished by placing the LEDs side by side and substantially aligned such that the limits of the light beams of each LED contain the common surface normal of each other light beam.

[058] The advantage of this multi-channel system is that different wavelength emission LEDs can be used to obtain the surface reflectance for the set of wavelengths produced by the LEDs at the time of the measurement.

[059] Because of the spectral sensitivity curve of LEDs, see Figure 6, it is preferred to use longer-wavelength LEDs as sensors and shorter-wavelength LEDs as emitters. This is because an LED used as a sensor in the method of this invention is much more sensitive to wavelengths equal to or shorter than the emission wavelength than to wavelengths longer than the emission wavelength.

[060] In the preferred embodiment, more than three LEDs are used. The light emitted by each LED can be sensed by any LED with an equal or longer wavelength and can act as a sensor for any other LED with an equal or shorter wavelength. As a result, having two LEDs emitting light at the very longest wavelength, such as using two infrared LEDs and a single LED of most other colors, provides the greatest span of wavelengths for sensitivity.

[061] Sensing Transmitted Light

[062] Figure 4A shows a schematic side-view of an embodiment of the invention as applied to a translucent, transparent, or opaque material between two LEDs. In this embodiment, the microcontroller 130 is connected to LEDs 410 and 411. In this arrangement of the invention, a light beam 420 that passes through a material under test 430. The material under test 430 may be a solid, a liquid, or a gas.

[063] In this embodiment, the LED 410 emits the light beam 420. The material 430 transmits the light to some extent, acting either transparently, translucently, or opaquely to transmit, partially, or completely absorb the light beam 420. The amount of light that passes through the material is then sensed by the LED 411. This embodiment can also use the differential method described above.

[064] As shown in Figure 4B, for materials with glossy surfaces or material contained in glossy containers, the material under test 430 can be at an oblique angle with respect to the light beam 420. This eliminates spurious light measurements due to specularities.

[065] Sensing Transmitted and Reflected Light

[066] Figure 5A shows an embodiment where both reflection and transmission are used. Here, the LEDs 501-503 are connected as described above. But in this embodiment, the test material 430 is placed between the LEDs 501-503 and a reflector 510 so that the incident light is perpendicular to the test material. The LEDs are positioned so that they are illuminated by specular reflection of any of

the other LEDS as reflected by reflective surface 510. This way, the light passes through the material two times.

[067] Sensing Backscatter

[068] If the desired measurement is to measure the turbidity or “backscatter” within the material under test, an oblique arrangement is preferred, as shown in Figure 5B. In this embodiment, a backing surface 520 is made of a light absorbing material that absorbs substantially all of the light passing through the material 430 under test. Additionally, note that the oblique arrangement shown in Figure 5B causes any light reflecting from any container or glossy surface containing the material 430 is not reflected back toward the LEDs.

[069] Figure 6 shows typical sensitivity curves 601-605 respectively for infrared, red, yellow, blue, and ultraviolet ‘colored’ LEDs. when used as sensors according to the invention. The curves indicate photocurrent on the vertical axis, and wavelength in nanometers. As can be seen by a sensitivity curve 610 for a 960-nanometer (infrared) LED, the photocurrent for any wavelength in the visible region is approximately constant. As the emitting wavelength decreases, say to 588-nanometer (yellow) LED, the sensitive to yellow, blue, and ultraviolet light remains constant, but the sensitivity to red (660nm) and orange (625nm) light is near zero. A 470-nanometer (blue) LED is sensitive only to blue and ultraviolet light. In the general case, an LED used as a sensor according to this invention should be considered to contain an intrinsic short-wavelength-pass filter.

[070] Figure 7 shows a fluorescence sensor 700 according to the invention. The microcontroller 130 and LEDs 701-702 are connected as described above. The LED 701 emits 710 is an ultraviolet light 710 at 370-nanometers or shorter, such as ATX corp. type BP-200CUV750-250. The LED 701 can be connected such that it is used only for emission, and never for sensing. Also in the preferred embodiment, LED 702 is used only for sensing, and is a long-wave sensitive LED, such as a 950-nanometer (infrared) or 639-nanometer (red) LED.

[071] LED 701 is arranged so that the emitted UV light 710 illuminates fluorescent material 730. The fluorescent material fluoresces under the ultraviolet light and emits visible light 720. The visible light 720 passes through a UV-blocking filter 740 and is detected by LED 702 in the manner described above. An opaque light shield 750 prevent any of the emitted UV light 710 from being sensed directly by the sensor LED 702.

[072] Although the invention has been described by way of examples of preferred embodiments, it is to be understood that various other adaptations and modifications may be made within the spirit and scope of the invention. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the invention.